Electromagnetic and Seismic Investigation of Methane Hydrates Offshore Taiwan – The Taiflux Experiment.

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***Abstract*—We report on an electromagnetic and seismic experiments carried out offshore Taiwan in April 2013 in the quest to quantify methane hydrate saturation (TAIFLUX project). The quantification of hydrates is essential to efficiently and cost effectively plan a drilling campaign and for a resource assessment of methane hydrates as an energy source to Taiwan. The work has been carried out in a collaboration of Taiwanese and German scientists and funding organizations. Preliminary and qualitative processing of seismic and electromagnetic data acquired on the Four-Way-Closure accretionary ridge situated on the active margin south-west of Taiwan shows the presence of hydrates and indication that hydrate concentrations are relatively high. We furthermore show that the derivation of quantitative hydrate concentration models from the data is difficult to achieve using either seismic or electromagnetic data alone. Best resolution and certainties in a hydrate concentration model may be achieved if both type of data sets are inverted together to a common model, since both types of data sets carry complementary information.**

Keywords—methane hydrates, marine electromagnetics, marine seismics, CSEM, P-cable seismics, joint inversion.

I. INTRODUCTION

The existence of gas hydrates South West of Taiwan have been inferred from a suite of seafloor observations and geophysical data sets [1] and stirred national Taiwanese interest to explore methane hydrates a as a potential energy source. In collaboration between Taiwan and Germany, a joint five-week geophysical cruise on the German research vessel Sonne has been staged in spring 2013 [2]. The overall goal was to map and understand the gas and fluid flow systems responsible for hydrate formation in two different tectonic settings, the passive margin towards the northwest and the subduction zone towards the southeast of Taiwan. The specific aim of the experiment is to map and quantify in detail methane hydrates within the sediments for these settings, information that is vital to understand the fluid and gas migration systems but also for energy resource assessment of gas hydrates.
Geophysical measurements sensitive to gas and hydrate distributions at depth in the sediments have been carried out in two locations (Figure 1) onboard the German research vessel Sonne (SO227) : On Formosa Ridge in an passive, erosional tectonic setting offshore the southern mainland China and on Four-Way-Closure in the active tectonic setting west of Taiwan, which is characterized by accretionary ridges. Within this abstract we will focus on work on the latter region.

II. GEOPHYSICAL DATA AT FOUR-WAY-CLOSURE

The Four-Way-Closure site includes a roll over anticline called Four-Way-Closure Ridge, which is the surface expression of an underlying blind thrust.

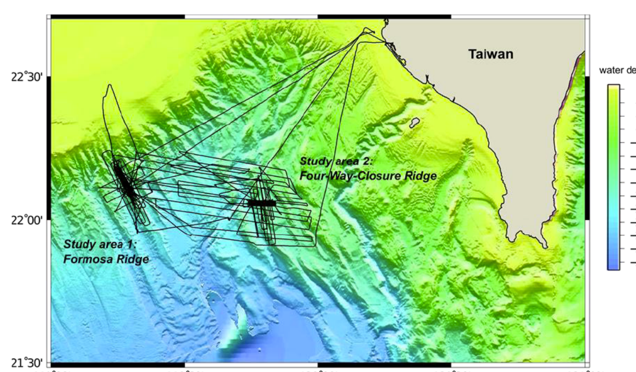

Fig. 1: Bathymetric map with cruise track of the German RV Sonne (SO227, 2.4.2013 Kaohsiung – 2.5.2013 Kaohsiung). Geophysical experiments to image fluid flow and methane hydrates have been carried out in two target areas representing an passive erosional setting (Formosa Ridge) and active accretionary setting (Four-Way-Closure).

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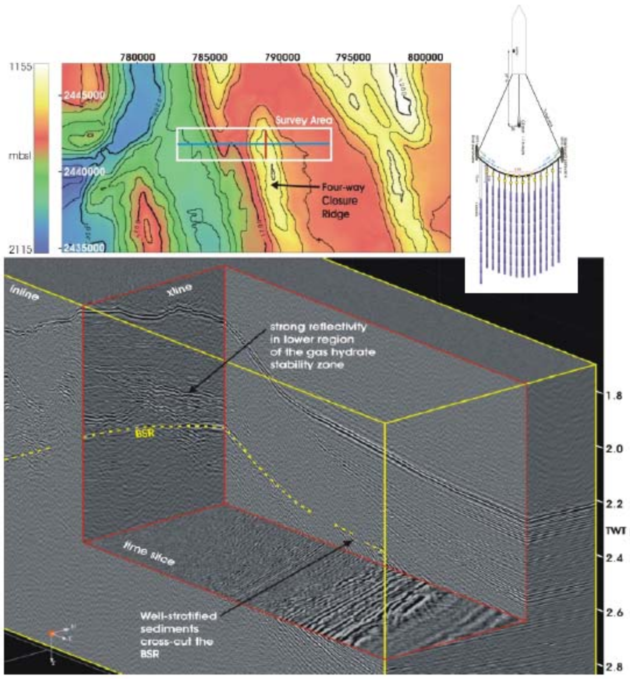

Fig. 2: Top: Bathymetry and survey outline of P-cable survey (left) and system configuration (right). Bottom: 3D "chair-cut" view into the 3D seismic data of the Four-Way-Closure Ridge study area. The bottom simulating reflection (BSR) is annotated, as are strong reflections above the BSR and reflections from well stratified sediments that cross-cut the BSR.

The comprehensive geophysical data set acquired includes high-resolution 3D seismic imaging with a P-cable system, ocean bottom seismometer (OBS) deployments, controlled source electromagnetic (CSEM) measurements, heat flow measurements, and ground-truthing using HyBis and TV grab. While the P-cable data allow us to determine the internal structure of the study areas down to a depth of approximately 500 m below sea floor, the OBS and CSEM data will constrain the hydrate and free gas saturation along two-dimensional transect through the 3D seismic cube. The heat flow data will be used to provide information on the thermal conditions of the sediments.

P-cable high resolution seismic data of Four-Way-Closure Ridge is depicted in Fig. 2. The presence of a strong BSR in the regions confirms the presence of methane hydrate. Above the BSR, packages of strong reflections in the lower gas hydrate stability zone are observed. Their presence suggests very high gas hydrate saturations and coeval presence of free gas and gas hydrate in the sediments.

East and west of the ridge, well-stratified sedimentary successions in the basins verge towards the ridge, cross-cutting the BSRs. While P-cable delivers high resolution information about sedimentary structure and existence of methane hydrate in the sediment, no velocity information and hence estimates of hydrate concentration may be deduced from the short offset data.

Since knowledge about the hydrate saturation is essential for appropriate choice of drill sites, complementary geophysical

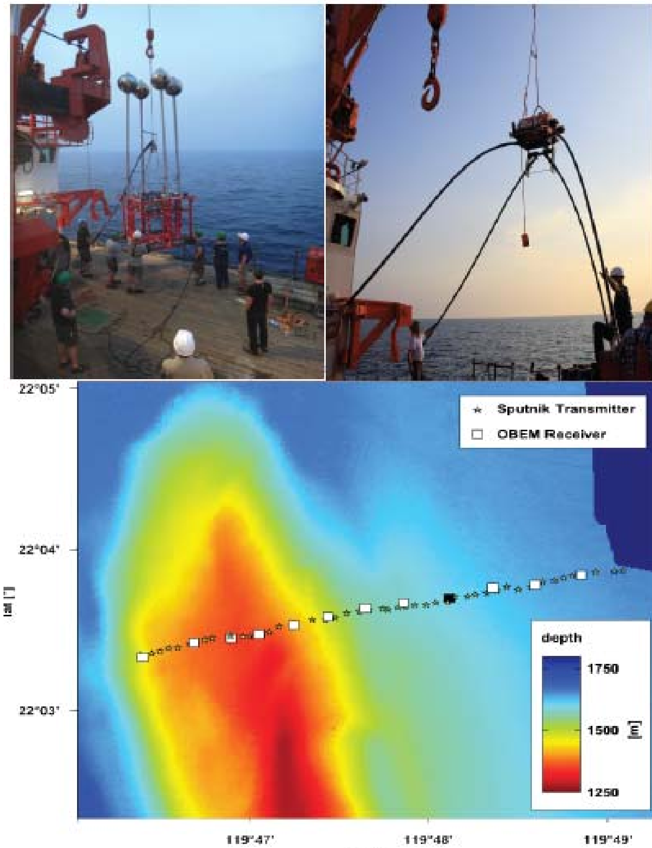

Fig. 3: Top: Time domain electromagnetic instrumentation: Left panel shows the Sputnik transmitter, which consists of two orthogonal dipoles, which unfold to a length of 10 m when the system is placed on seafloor. The transmitter signal consists of a bi-polar square wave of 50 A amplitude and a 50% duty cycle. The transmitter is placed on the seafloor, delivers a transmission cycle and is then moved to the next station. Right panel shows one of the 12 electromagnetic receivers which have been placed stationary on the seafloor and have sampled the electric field at 10 kHz by two orthogonal dipoles. Lower panel depicts the CSEM profile.

data such as OBS and CSEM data, which are more sensitive to hydrate concentration (alas characterized by less structural resolution), have been recorded. Of particular interest is the measurement of electrical resistivity distributions, since this parameter increases strongly when the normally well conducting fluid filled pore space is reduced due to increasing amount of electrically isolating hydrate or gas in the pore volume [3]. Fig. 3 shows the CSEM system used in the experiment [4], which has been developed at GEOMAR over the last few years and differs from conventionally used marine EM systems [5]. Its novel aspects are that it a) uses two orthogonal transmitter dipoles and receivers dipoles thus providing information about subsurface resistivity for two polarization modes and b) works in the time domain and records data for various transmitter-receivers offsets thus ensuring a better coverage and resolution of the subsurface then conventionally used marine CSEM systems. Due to the fact that transmitter and receiver are stationary on the seafloor during transmission, we get an optimal coupling of the signal into the ground and are also able to record data in locally rough topography, with slopes approaching values of 45°.

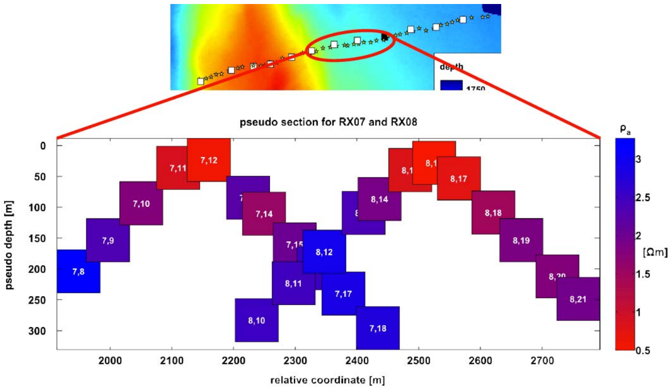

Fig. 4: Preliminary apparent resistivity section derived from transmissions to 2 seafloor receivers. Apparent resestivities [6] have been derived for various TX-RX offsets and are plotted at a depth of half the according horizontal offset..

A first preliminary apparent resistivity section could be derived from rotational invariants of the data [6] to the east of the Four-Way-Closure summit and is shown in Fig. 4. The relatively high values of apparent resistivity generally suggest high hydrate concentrations. Apparent resistivity sections derived from the data on the summit show the presence of an even higher resistive zone, however, these results may be biased by the strong topography in the vicinity which invalidates plane surface assumption made in the derivation of apparent resistivities, such that further evaluation need to take place before conclusions can be drawn.

In summary the preliminary data evaluation of the SO227 cruise P-cable and CSEM data thus confirms the presence of methane hydrates (through observation of BSR in the P-cable data) and probably high concentration of methane hydrates, as well as highly resistive features derived from the CSEM.

III. Concepts of Data Interpretation Schemes

In order to derive the desired hydrate concentrations as function of space in the target area in the future, all available geophysical information will have to processed fully and eventually pulled together in order to interpret the data. While each of the data set recorded contains pieces of the desired information such as sensitivity to hydrate concentration (CSEM and OBS data) or structural resolution (P-cable data), no method, if taken by itself, is able to yield the desired high resolution and quantitative hydrate model by itself.

Quantification furthermore requires a conversion of the physical parameter measured (i.e. velocity, electrical resistivity) into hydrate concentration. The transformations may either be carried out using experimentally derived relations (from borehole or laboratory results) or through effective medium theory and the results therefore depend on the 'best guess' choice of the transformation to be used depending on background information of the setting as well as available data.

The uncertainties in gas hydrate models may be mitigated by interpreting different geophysical data sets in a combined

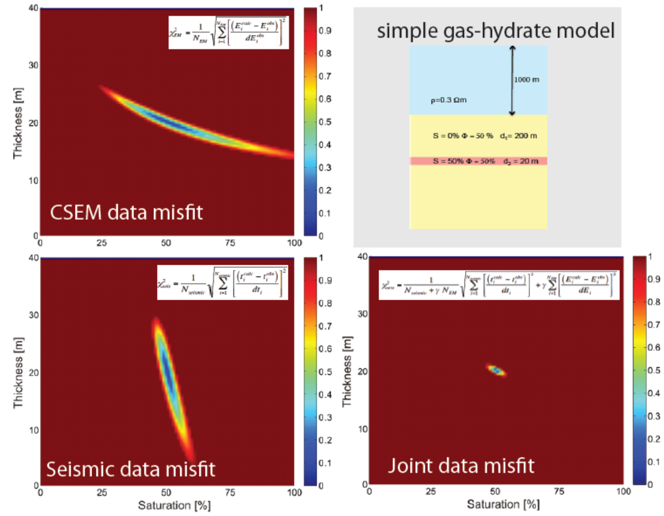

Fig. 5: Assuming a simple layered gas hydrate model presented in top-right model, physical parameters such as p-wave velocity and electrical resistivities have been derived. Based on the physical parameter models seimsic reflection data as well as CSEM data have been generated onto which we added Gaussian noise. Assuming that the depth to the hydrate layer as well as the background physical model is known, top left panel shows the normalized χ^2 misfit of the generated data with data generated for various thickness – hydrate staturation models. Non-red values show areas of small misfit indicating the model space which fits the CSEM data. Bottom left shows the type of calculations for the seismic reflection data. The model space fitting the data can be greatly reduced if a joint misfit function for CSEM and seismic data is formulated, indicating that a joint-inversion procedure may increase resolution and certainty of hydate quantification.

fashion. Current strategies of integrating results from different methods consist of the comparison of individual Earth models derived from different data sets and/or using Earth models derived from one method as an a-priori constrain for the inversion of other types of data. The final, resulting hydrate concentration model however will be dependant on the chosen sequence of data integration, choice of parameter transformation to hydrate concentration and ultimately by the experience and personal bias of the particular interpreter. It also contains very little reliable statistical information about errors in the hydrate quantification.

A key strategy to improve on some of these issues is the joint inversion strategy, which we want to present here. In joint-inversion [7] already in the statistical process of identifying Earth models fitting the observed data, only methane hydrate distributions, which fit all the different data sets, are included in the search process. Fig. 5 shows exemplarily for a very simple model, how the joint inversion strategy works compared to single data type inversion. The model consists of a thin hydrate layer (50 m thickness) buried at 200 m depth under in the sediments. The sediment itself is assumed to have a porosity of 50%, which is filled with salt water. Within the hydrate layer, half of the pore-space is occupied by methane hydrate instead of pore water fluid. Based on this model, resistivity and p-wave velocities have been derived using effective medium theory and synthetic CSEM and seismic reflection data generated, on which 5% Gaussian noise has been added. Inversion of these particular data to a model should give us some indication on how well we can actually recover a quantified hydrate concentration model from the data. Inversion itself implies the search of a model, whose response fits best to a predefined level with the observed data (minimal $\chi 2$ misfit). This minimal misfit model is usually found by assuming a start model and an iterative walk through the model space along a path defined by the condition that at each step the misfit should decrease. Even if we assume that we know a) depth to the hydrate layer, b) parameter transformation between physical parameter and hydrate saturation and c) physical parameter of the back ground model and we are only requesting information about the thickness and hydrate concentration from the data, still a variety of models, which fit the data equally well, exist for reflection seismic and electromagnetic data inversion as shown in Fig. 5. However the solution spaces differ for each method, indicating that complementary information about hydrate concentration and layer thickness is contained in the different data sets. Therefore the solution space for a joint inversion is much smaller. In order to derive high resolution hydrate estimations our results indicate that it is preferable to steer the iterative path through the model space in an inversion using a joint-misfit functions. At GEOMAR, we have developed this kind of joint-inversion algorithms for layered models for CSEM and various typed of seismic data and want to apply this type of methodology to our CSEM and seismic data acquired offshore Taiwan.

IV. Conclusion and Outlook

Within the TAIFLUX project high resolution seismic and CSEM data have been acquired. On Four-Way-Closure Ridge, a preliminary first processing of the data indicated the presence of methane hydrate at high concentrations. While each data set contains information about the hydrate concentrations in the subsurface, a quantitative high resolution methane hydrate saturation cannot be derived from each individual data sets but require the use of joint-inversion strategies as presented in this paper.

This work has been sponsored by the German ministry of Education and Research (BMBF) and the Taiwanese National Science Council (NSC).

V. Acknowledgments

This work is funded by the German Ministry of Education and Research (BMBF) and the Taiwanese National Science Council (NSC).

VI. References

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